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A METHODOLOGY FOR UPDATING THE NAVY'S LOGISTICS FACTORS FILE

by

Raymond John Benedict

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Thesis Advisor: Robert Read

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A METHODOLOGY FOR UPDATING THE NAVY'S LOGISTICS FACTORS FILE

Raymond John Benedict
Lieutenant, United States Navy
B.S., United States Naval Academy, 1989

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Author: Raymond John Benedict
Raymond John Benedict

Approved by: R R Read
Robert Read, Thesis Advisor

Dan C Boger
Dan Boger, Second Reader

Frank C. Petho
Frank Petho, Chairman
Department of Operations Research

ABSTRACT

This thesis develops a methodology for updating the Navy's Logistics Factors File, which has been neglected in recent years and requires updating. This study is limited to Repair Parts (Class IX of the Department of Defense Supply Class Codes) for the following four classes of ships: CVN-68 (Nimitz class) Aircraft Carriers, CG-47 (Ticonderoga class) Guided Missile Cruisers, DD-963 (Spruance class) Destroyers, and FFG-7 (Oliver Hazard Perry class) Guided Missile Frigates.

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LIST OF ACRONYMS

ABFC - Advanced Base Functional Component

AMC - Air Mobility Command

ARG - Amphibious Ready Group

BDR - Battle Damage Repair

BG - Battle Group

CDF - Cumulative Distribution Function

CINC - Commander in Chief

CJCSM - Chairman of the Joint Chiefs of Staff Manual

CLF - Comvat logistics Force

CONPLAN - Operation Plan in abbreviated Concept Format

CONUS - Continental United States

CRAF - Civil Reserve Air Fleet

CVBG - Carrier Battle Group

DLA - Defense Logistics Agency

DoD - Department of Defense

ECDF - Empirical Cumulative Distribution Function

GEOLOC - Geographic Location

HNS - Host Nation Support

ICP - Inventory Control Point

JCS - Joint Chiefs of Staff

JFAST - Joint Flow and Analysis System for Transportation

JOPES - Joint Operation Planning and Execution System

JPEC - Joint Planning and Execution Community

JSCP - Joint Startegic Capabilities Plan

K-S - Kolmogorov-Smirnov

LFF - Logistics Factors File

LOGFACREP - Logistics Factors report

LOGGEN - Logistics Generator

LOGSAFE - Logistics Sustainment Analysis and Feasibility Estimator

MCB - Mobile Construction Battalion

MLE - Maximum Likelihood Estimator

MRG - Movement Requirements Generator

MSC - Military Sealift Command

MTMC - Military Traffic Management Command

NIIN - National Item Identification Number

NPS - Naval Postgraduate School

NRG - Notional Requirements Generator

NSC - National Security Council

OPLAN - Operation Plan

PDF - probability density function

POSF - Port-of-Support File

PRC - Potomac Research Corporation

RDD - Required Delivery Date

RSSP - Ration Supplement Sundry Packs

SPCC - Ships Parts Control Center

SRF - Standard Reference File

SYSCOM - Systems Command

TPFDD - Time Phased Force and Deployment Data

TUCHA - Type Unit Characteristics File

UIC - Unit Identification Code

USCINCTRANS - Commander in Chief, United States Transportation Command

USTRANSCOM - United States Transportation Command

UTC - Unit Type Code

WWMCCS - Worldwide Military Command and Control System

EXECUTIVE SUMMARY

This thesis develops a methodology for updating the Navy's Logistics Factors File (LFF), which has been neglected in recent years and requires updating. The LFF contains logistics consumption planning factors for all units in the Navy by Class/Subclass of supply. It is used to predict unit sustainment requirements in support of Joint Operation Plans, crisis action planning, logistics feasibility estimation, and for wargaming analysis. This thesis is limited in scope to modeling only repair parts for the following four classes of ships: CVN-68 (Nimitz class) Aircraft Carriers, CG-47 (Ticonderoga class) Guided Missile Cruisers, DD-963 (Spruance class) Destroyers, and FFG-7 Oliver Hazard Perry class) Guided Missile Frigates. Department of Defense guidance defines repair parts as Class IX, which is further subdivided into different subclasses.

The current LFF structure includes a single data entry (in pounds per unit per day) to describe the sustainment requirements of these units for all of the Supply Classes and their respective Subclasses. For Repair Parts, these values are severely understated when compared to contemporary data. These "pounds per unit per day" random variables have severe positive asymmetries. These distributions can be fitted with mixtures of skewed probability distributions in order to achieve more reliable consumption figures. It is also wise to recommend associated variability information be included either directly in the LFF, or in a readily available companion source. The results obtained from using mixed distributions are exhibited alongside the current factors in the Table on the following page to illustrate the significant differences between the two:

Subclass	Current CVN-68 Factor	New CVN-68 Factor	Current CG-47 Factor	New CG-47 Factor	Current FFG-7 Factor	New FFG-7 Factor	Current DD-963 Factor	New DD-963 Factor
IX(A)	326.00	242.43	1.00	0.25	0.00	0.22	0.00	0.14
IX(B)	78.00	616.36	7.00	61.71	1.00	49.31	7.00	34.57
IX(D)	3.00	1.67	1.00	0.03	0.00	0.03	0.00	0.02
IX(G)	234.00	8211.91	19.00	496.23	8.00	321.40	23.00	463.95
IX(K)	59.00	N/A	6.00	N/A	3.00	N/A	4.00	N/A
IX(L)	16.00	3.07	0.00	0.34	0.00	0.16	0.00	0.15
IX(M)	6.00	98.94	0.00	2.09	0.00	0.99	0.00	1.19
IX(T)	623.00	1041.45	37.00	19.61	9.00	7.00	17.00	7.64
TOTAL	1345.00	10,215.8	71.00	580.26	21.00	379.11	51.00	507.66

Table Comparing Current Factors in Navy LFF To New Factors Derived from Recent Historical Data and Mixed Probability Distributions. All factors in pounds per unit per day.

The methodology developed in this thesis fits mixtures of probability distributions to historical data collected from the supply requisitions of Naval surface combatants over a three year period. Analysis performed on this data yields new factors which may be used to update the Navy's LFF. The use of mixtures is recommended because of the substantial number of days where no requisitions occur, as well as the infrequent yet critical days where requisitions of 'extreme' weight occur.

There are several caveats that must be understood by potential users of these new factors. These are explained in the development of the methodology and summarized in the conclusions. One of the main difficulties in the study was the discovery of missing weight data on many of the items that had been requisitioned during the data collection time frame. The other significant difficulty was the method of accounting for the extremely large requisition weights. Developing the methods

to correct these difficulties, as well as other, smaller ones, is a critical part of the methodology developed by this study.

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I. INTRODUCTION

This thesis fits mixtures of probability distributions to historical data taken from the supply requisitions of U.S. Navy surface combatants. The intent of this thesis is to devise a methodology for analyzing this data to update the Navy's Logistics Factors File (LFF). The scope of this thesis is limited to modeling only repair parts for four common classes of warships. The use of mixtures is recommended because of the substantial numbers of days where no requisitions were submitted, as well as the infrequent yet critical days where requisitions of 'extreme' weight occurred. The results obtained from using the mixed distributions are exhibited in Table 1 on the following page. However, there are many caveats that must be understood by potential users of the Table. These are explained in the development of the methodology and summarized in the conclusions.

One of the main difficulties in the study was the discovery of missing weight data on many of the repair parts requisitioned during the data collection time frame. This problem, and how it was handled, is discussed in Section A of Chapter III. The other significant difficulty was the method of accounting for the outliers, or days with extremely large requisition weights. This issue is addressed in Section B of Chapter IV.

Other aspects of the organization of this thesis are as follows: Chapter II contains general background information on the critical role of the LFF in Joint Operation Planning. More specific details about the Navy's perspective with regards to the LFF and the Department of Defense (DoD) system of classifying Supply goods are contained in Chapter III. Data collection, manipulation, and the methods of analysis are in Chapter IV. These are followed by results of the study in Chapter V, and Conclusions in Chapter VI. Several

appendices are included to document specific details of the data analysis phase.

Subclass	Current CVN-68 Factor	New CVN-68 Factor	Current CG-47 Factor	New CG-47 Factor	Current FFG-7 Factor	New FFG-7 Factor	Current DD-963 Factor	New DD-963 Factor
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Table 1. Comparison of Current Factors in Navy LFF To New Factors Derived from Recent Historical Data and Mixed Probability Distributions. All factors in pounds per unit per day.

II. THE ROLE OF THE LFF ON JOINT OPERATION PLANNING

Logistics is defined as "the science of planning and carrying out the movement and maintenance of forces." Military planners focus on logistics processes and products with the objective of achieving and sustaining operational readiness. In general, the mission of naval logistics is "to provide and sustain our operational readiness by getting the right support to the right place at the right time" [Ref 1].

The six functional areas of logistics are considered to be: supply, maintenance, transportation, engineering, health services, and other services. Successful military planning involves careful integration of all six functional areas [Ref 2]. Of these six functional areas,

> Transportation has been a critical factor in strategy since fighting men carried equipment on their backs and lived off the countries where they were engaged. It has grown more important as the scope of hostilities has widened, and the burden of military equipment and supplies has increased [Ref 3].

Transportation resources are required to support mobilization, deployment, employment, sustainment, redeployment, and demobilization operations [Ref 4]. In short, no operation can succeed without transportation.

A 1994 Joint Chiefs of Staff (JCS) Deliberate Planning Conference concluded a need existed for the services to conduct a review of their LFFs. The LFF is one of several Standard Reference Files (SRFs) within the Joint Operation Planning and Execution System (JOPES), which supports planning and sustainment of forces. The LFF provides logistics consumption factors by class/subclass of supply for each unit in the Type Unit Characteristics

(TUCHA) file, another JOPES SRF. (Table 2 on pages 11-12 lists the ten DoD supply classes and their respective subclasses.) These logistics consumption factors can be used in logistic feasibility estimation, wargaming analysis, or to produce a Time Phased Force and Deployment Data (TPFDD) database, which helps determine logistics sustainment requirements in the development of an Operation Plan (OPLAN). The conclusion of the JCS conference was that existing factors were outdated and unreliable, invalidating logistics sustainability analyses [Ref 5]. Those familiar with DoD transportation systems and planning methods may choose to bypass the remainder of this chapter, which provides background on these issues and the importance of an accurate LFF.

A. UNITED STATES TRANSPORTATION COMMAND

The US Transportation Command (USTRANSCOM) is a single, unified command whose mission is "to provide strategic air, land, and sea transportation to deploy, employ and sustain military forces to meet national security objectives across the range of military operations" [Ref 6]. Combatant commanders inform the Commander in Chief, U.S. Transportation Command (USCINCTRANS) of their movement requirements and required delivery dates (RDDs). USTRANSCOM then provides strategic lift through its three service component commands: Air Mobility Command (AMC), Military Sealift Command (MSC), and Military Traffic Management Command (MTMC).

AMC, a responsibility of the Air Force, manages strategic airlift. U.S. war plans have traditionally required 5% of the highest priority cargo, mail and passengers to be airlifted into theater. Additionally, due to its speed and flexibility, airlift will be combined with pre-

positioned assets to transport the initial U.S. forces deploying into a theater of conflict [Ref 7]. The role of strategic airlift is limited by cost and capacity. For example, a typical strategic airlift mission from Operation Desert Shield/Storm consumed almost one million pounds of fuel and cost $280,000 [Ref 8]. The capacity limitations of strategic airlift are further constrained by the fact that only 20% of airlift capacity is contained in active duty forces. The other 80% is shared by reserve components (30%) and the commercial sector (50%), supported by the Civil Reserve Air Fleet (CRAF) [Ref 7].

MSC is managed by the Navy and provides strategic sealift, which is relatively inexpensive and has the highest capacity. Sealift has traditionally provided 95% of all strategic lift during force mobilizations. While the capabilities of airlift have improved, sealift still transported 90% of all materiel during Operation Desert Shield/Storm [Ref 1]. However, despite vast upgrades to U.S. sealift capability during the 1980s, we still had to charter over 70 foreign flagged vessels to support sealift requirements during Desert Shield. Much like airlift, only 20% of sealift capability is assigned to active duty forces. The other 80% is covered by the commercial sector [Ref 7].

The Army is responsible for MTMC, the third component of USTRANSCOM. MTMC manages ground transportation (truck and rail) within the Continental U.S. (CONUS), as well as most U.S. military ocean terminals [Ref 6]. In the event of a large scale mobilization of forces, MTMC assets would be involved in both the initial surge of troops and supplies as well as the follow-on sustainment of those forces.

B. JOINT OPERATION PLANNING

Joint operation planning involves the preparation and execution of plans for potential crises that involve military forces. The President of the United States directs the National Security Council (NSC) to establish national security procedures, including mobilization, to the DOD. From these directives, the Joint Planning and Execution Community (JPEC) plans for the mobilization, deployment, employment, sustainment, redeployment, and demobilization of joint forces [Ref 4].

Within the classification of joint operation planning are two classes of structured, formal processes: deliberate planning and crisis action planning. Crisis action planning is more reactive, usually carried out in response to a specific situation. Though crisis action planning develops in a very short time period, usually days or even hours, logistics requirements must still be met. Deliberate planning involves the entire JPEC community, and can take 18-24 months to fully develop [Ref 9]. The LFF is used in both methods of planning to validate transportation feasibility estimates and ensure forces can be adequately sustained.

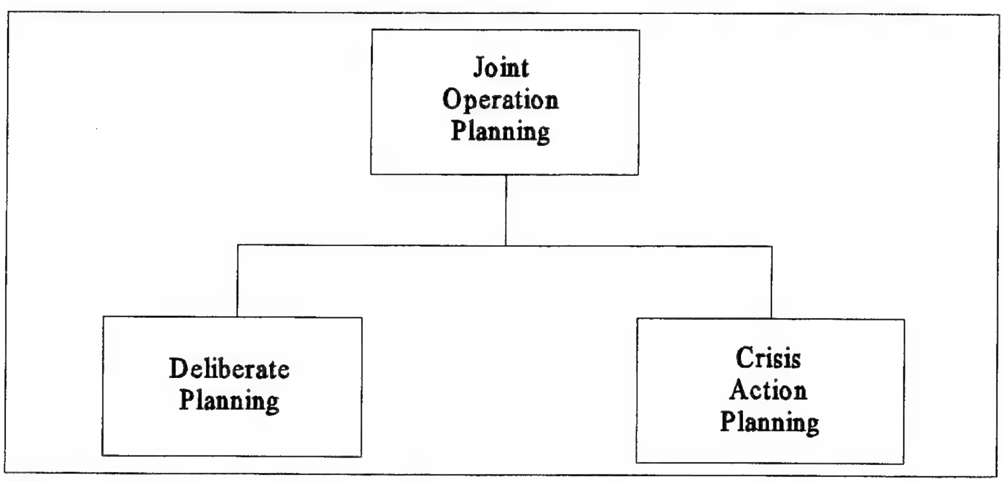

Figure 1. Classes of Joint Operation Planning.

USTRANSCOM conducts detailed transportation feasibility analysis during both deliberate and crisis action planning using the Joint Flow and Analysis System for Transportation (JFAST). JFAST is used during crisis action planning by providing information on transportation assets needed to move and resupply forces, as well as interpret shortfalls and assist in reallocating lift. Logistics planners only have to provide major units to be involved along with associated planning factors from the LFF. JFAST then uses its Notional Requirements Generator (NRG) to calculate combat support, combat service support, and non-unit cargo requirements. These requirements are then used to estimate the associated transportation requirements [Ref 10].

Fundamental to the deliberate planning process is the Joint Strategic Capabilities Plan (JSCP), which tasks the combatant Commanders-in-Chief (CINCs) with preparing plans in support of national security objectives. There are four types of deliberate plans that can be prepared based on JSCP requirements. The type of plan developed is based on the level of detail required and purpose of the plan, as is shown in Figure 2 [Ref 11].

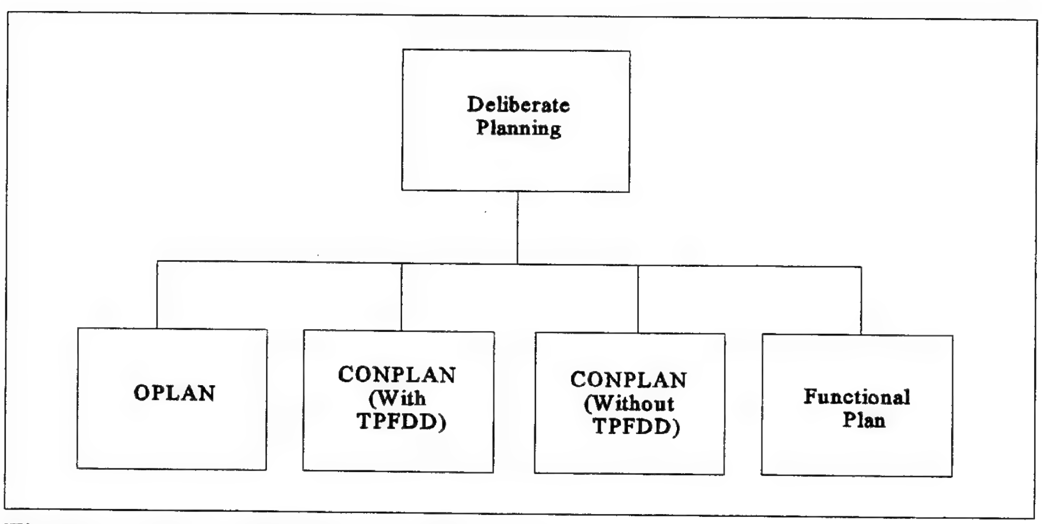

Figure 2. Types of Deliberate Planning.

The most complete and detailed joint operation plan is called an OPLAN. "OPLANs are normally prepared when the contingency has a compelling national interest and a specific threat, and the large scale of the contingency requires detailed prior planning for complex issues" [Ref 9]. Because OPLANs are so detailed and complex, the JOPES system which processes them requires many annexes and appendixes, including a TPFDD. A CONPLAN is a joint OPLAN in abbreviated concept format. Depending on the level of detail required by the JSCP, a CONPLAN may or may not contain a TPFDD [Ref 11]. The LFF plays a crucial role in the development of OPLANs and CONPLANs (with TPFDDs), but is also used by JFAST to estimate lift requirements for CONPLANs (without TPFDDs) and Functional Plans.

Ref 12, Joint Pub 5-03.1 "Joint Operation Planning and Execution System, Vol I", defines a TPFDD as:

> The JOPES data base portion of an operation plan; it contains time-phased force data, non-unit-related cargo and personnel data, and movement for the operation plan, including:
>
> - In-place units.
> - Units to be deployed to support the operation plan with a priority indicating the desired sequence for their arrival at the port of debarkation.
> - Routing of forces to be deployed.
> - Movement data associated with deploying forces.
> - Estimates of non-unit-related cargo and personnel movements to be conducted concurrently with the deployment of forces.
> - Estimate of transportation requirements by common-user lift

> resources, as well as those requirements that can be fulfilled by assigned or attached transportation resources.

After planning movement requirements and the time-phased sequencing of forces into the theater, the TPFDD shows for the quantities of supplies that will be required to sustain those forces. These supplies are then also phased into the theater. The final phase in developing a TPFDD is validating the plan by simulating the force movements. In the event that no feasible strategic lift deployment can be derived, then shortfalls must be resolved by adjusting the movement requirements. The CINCs then determine whether such adjustments pose acceptable or unacceptable risks [Ref 9].

JOPES uses a modeling system called Logistics Sustainment Analysis and Feasibility Estimator (LOGSAFE) to provide feasibility estimates and generate resupply requirements. In doing so, LOGSAFE uses the LFF, TUCHA, Ports-of-Support File (POSF), Geographic Location File (GEOLOC), OPLAN TPFDDs and user-specified parameters [Ref 10]. Since transportation is such an important fundamental of logistics, and good logistics planning is essential to any military campaign, planners need an accurate LFF to plan for any contingency.

III. THE NAVY'S LOGISTICS FACTORS FILE

The primary purpose of the LFF is to predict resupply planning factors for Navy and Marine Corps units. These factors must be accurate enough to ensure proper joint operation planning. The following list describes several reasons for maintaining an accurate LFF:

A. Predicting sustainment requirements of non-unit related cargo for feasibility analysis of OPLANs.

B. Defining the lift footprint (i.e., the impact of strategic lift capabilities) for determining amphibious lift requirements in support of future shipbuilding programs.

C. Identify shortfalls in current OPLANs and reapportion supplies to correct them.

D. Assess strategic lift requirements for apportioning limited sealift and airlift assets to commanders.

E. Determine the required quantity and composition of prepositioned supplies to maximize effectiveness.

F. Determine requirements for Host Nation Support (HNS) to meet identified shortfalls [Ref 10].

Table 2 lists the ten DoD classes of supply and their various subclasses [Ref 13]:

CLASS	SUBCLASSES
I. Subsistence (food)	A - Nonperishable dehydrated subsistence C - Combat rations requiring no organized dining facility R - Refrigerated subsistence S - Nonrefrigerated subsistence (less other subclasses) W - Water

CLASS	SUBCLASSES
II. General support items: Clothing, individual equipment, hand tools, administrative, housekeeping supplies, etc.	A - Air B - Ground support material E - General supplies F - Clothing and textiles G - Electronics M - Weapons T - Industrial supplies
III. POL (Petroleum, Oils & Lubricants):	A - Air (JP-5) W - Ground (Surface) P - Packaged POL
IV. Construction & barrier materials.	A - Construction B - Barrier materials
V. Ammunition: Ammunition of all types	A - Air W - Ground
VI. Personal demand items: Non-military sales items.	A - Non-packaged personal demand items M - Personal & Official letters and packaged mail P - Ration Supplement Sundry Packs (RSSP)
VII. Major end-items	A - Air B - Ground support material (generators, fire-fighting,etc) D - Admin & general purpose vehicles G - Electronics K - Tactical and special purpose vehicles L - Missiles M - Weapons
VIII. Medical material	A - Medical material B - Blood and fluids
IX. Repair parts	A - Air B - Ground support material (generators, firefighting, etc) D - Administrative vehicles G - Electronics L - Missiles M - Weapons T - Industrial supplies
X. Other	NONE

Table 2. Classes and Subclasses of Supply

A. PROBLEMS WITH EXISTING LOGISTICS FACTORS FILE

Despite its importance to operational planning, there are many shortfalls currently inherent to the Navy LFF. The following discussion of shortfalls was produced by the Potomac Research Corporation (PRC), Inc., in their second Interim Report for improving, validating and maintaining the LFF for the Navy [PRC, 1995].

1. Outdated Guidance

The joint directive which provides the services specific guidance on providing inputs to the LFF is the Logistic Factors Report (LOGFACREP), which was issued in 1985. The Chairman of the Joint Chiefs of Staff Manual (CJCSM) 3150.23 updates the LOGFACREP and recommends significant changes to the LFF. If these recommendations are approved, planning cycles will decrease from two years to one year, necessitating a simpler structure for the LFF, including the elimination of having to "source" where non-unit related supplies come from.

2. Non-Standard Models for Generating Sustainment

Since the late 1970s, records for TPFDDs have been developed by a system called the Movement Requirements Generator (MRG). In 1992, LOGSAFE was fielded as the replacement for the MRG and installed on the Worldwide Military Command and Control System (WWMCCS). While LOGSAFE is now the official model for generating TPFDD records, many planners on unified and service component command staffs still prefer to use MRG or a third model called Logistics Generator (LOGGEN), because they are easier to use or provide more details. This is permissible because of a loophole in the joint guidance which allows the use of other systems which provide similar data and analysis.

3. Lack of Information on the LFF

The only published material that PRC, Inc., could find which provides any background information on the LFF was the old LOGFACREP. No information could be found describing the source of the intensity rates used by the LFF or the methodology employed (such as pounds per man per day for a given subclass of supply). Even the Joint Publications which describe the JOPES system (Joint Pubs 5-03.1 and 5-03.2) do not provide any of this background information. Hence, no insight could be determined as to why it is set up the way it is.

4. No Routine Update Process for the Navy

Original Navy logistic planning factors were produced from a 1979 study entitled "*An Analysis of Navy Logistic Planning Factors*", dated 30 November 1979. Many of those factors still reside in the current Navy LFF. A partial update of the Navy LFF was conducted in 1989 by the David Taylor Naval Research Center. Based on historical requisition data collected from deployed surface and aviation units, this appears to be the Navy's most recent update. Despite the updated factors, this report was neither approved nor released, and none of the participants of that study could be contacted, so the exact methodology used by the study is unknown.

5. Questionable Validity of Current Factors

In addition to the current Navy factors being outdated and derived from unknown methods, their very low values question their accuracy. For example, the current factor for an FFG-7 Guided Missile Frigate, class IX(G) (Repair Parts, Electronics), moderate intensity, European conflict scenario is 14 lbs per day. Historical data collected by the Ships Parts

Control Center (SPCC), Mechanicsburg, PA, reveals days where this type of unit requisitioned over 100,000 Lbs of this subclass. This magnitude of error is not limited to this class/subclass of supply, nor to this class of ship.

6. Navy Uses Different Resupply System than Other Services

It is important to note that the LFF is used to generate non-unit related cargo requirements. Non-unit related cargo is defined as "All equipment and supplies requiring transportation to an area of operations, other than those identified as the equipment or accompanying supplies of a specific unit" [Ref 12]. The TPFDDs generally address only the first 90 days of an OPLAN, during which most of the common user strategic lift provided by USTRANSCOM is dedicated to the Army (80%) and the Air Force (10%). These two services generally deploy with only three days of sustainment. Because of their need to be resupplied almost immediately after deploying, these services use a "push" system which provides resupply until a regular requisitioning system can be established.

In contrast, Naval forces typically deploy with six months of sustainment carried by the combatant ships and the Combat Logistics Force (CLF) support ships. There are some notable exceptions to this policy, such as the Mobile Construction Battalions (MCBs) and Advanced Base Functional Components (ABFCs), but it applies to the Navy component of Amphibious Ready Groups (ARGs) and Carrier Battle Groups (CVBGs). This six months worth of sustainment is considered unit-related cargo because it accompanies the units. Hence, the Navy utilizes a "pull" resupply system, whereby it requisitions only what it needs as it operates. Naval forces still require sustainment, especially certain types of munitions, but this does not amount to a significant portion of common user strategic lift assets.

While this discussion may appear to lessen the importance of the Navy LFF with regards to joint operation planning, quite the opposite is true, especially for Class IX (repair parts). The Navy's Class IX factors must be capable for use in the prediction of the sustainment requirements of repair parts that will be requisitioned for Battle Damage Repair (BDR). In such a case, such as a ship contacting a mine or being struck by a cruise missile, it is highly unlikely that it can be repaired using only assets carried by the Battle Group (BG). More likely, thousands of pounds of repair parts would have to be lifted into the theater to conduct the necessary repairs. Additionally, no ship or BG can be expected to carry enough of every spare part to account for every conceivable equipment casualty that a ship could suffer during a wartime deployment. The high priority that would be assigned to any repair part(s) needed to restore a ship to operational readiness would necessitate the part(s) being airlifted, and airlift assets will probably be in more demand than sealift. LFF sustainment rates are also used when planning logistics sustainment requirements for wargames.

7. Navy Does Not Use DoD Class/Subclass Supply System

Each subclass of supply listed in Table 2 has a consumption factor associated with it. It is difficult for the Navy to develop factors in this fashion because the Navy supply system does not assign items by class/subclass. Instead, the Navy has traditionally classified its sustainment supplies in the following broad categories: ordnance, fuel, dry cargo, wet cargo and refrigerated cargo. Navy supply infrastructure is decentralized to assorted System Commands (SYSCOMS), which assign personnel to manage certain assets. Because of this setup, the Navy cannot specifically manage supply by the DoD class/subclass system. The method that the Navy has devised to get around this problem is a critical part of the

methodology of this study, and it is discussed in Chapter IV.

8. Inaccurate Supporting Files

The LFF is used in conjunction with the TUCHA, which provides the Unit Type Code (UTC) for notional units. Each service is responsible for maintaining the data in their respective TUCHAs, but until recently the Navy has done a poor job of updating. PRC, Inc., found examples of UTCs with had consumption rates in the LFF that were not listed in the TUCHA, as well as UTCs in the TUCHA with no sustainment factors in the LFF. Additionally, the Navy TUCHA listed non-deployable units that would never require consumption rates, such as a Coast Guard District Headquarters. The Navy and Marine Corps even had different units in the TUCHA with the same UTC. Finally, as entire ship classes and aircraft squadrons are decommissioned, as well as new ship types are introduced (such as the DDG 51 and LHD 1 classes), a need exists to establish a system which periodically reviews and updates the TUCHA.

Another area where incomplete data files hinder the Navy's ability to maintain an accurate LFF is the lack of weight and cube (volume) information on items in the Navy and DoD supply inventories. The problems this causes will be discussed in detail in Chapter IV, but it should be apparent that it is impossible to develop consumption rates (in units of lbs per UTC per day) if the weights of the supply items are unknown. The Navy supply system listed 469,361 items in its inventory (listed by National Item Identification Number, or NIIN). Only 254,221 of these items (54.2%) had a weight assigned, while the other 215,140 had zeroes listed. The Defense Logistics Agency (DLA) did only slightly better, with actual weights assigned to 2,039,158 items out of 3,533,161 (57.7%). The remaining 1,494,003 items were

assigned weights of zero.

9. No Consideration for Variance of Consumption Factors

The factors listed in the LFF are point estimates of some central value, though it is unknown exactly what these numbers represent. They could be the mean or median values from some set of historical data, or even a best guess from someone with experience in this field. Regardless of how these numbers were derived, there is no consideration given to the very large variances that are involved. An example of the magnitude of this variance is cited in Subsection 5 of the present Chapter.

B. THESIS OBJECTIVES

The Navy is currently working to improve many of the problem areas discussed in Section A of this Chapter. Examples of these efforts include:

- Reviewing and providing comments on the draft of the new CJCSM 3150.23 Joint Reporting Structure (LOGFACREP) to improve the process of Service inputs to the LFF.
- Establishing a routine process for maintaining the LFF.
- Updating supporting files, such as the TUCHA.
- Developing a procedure to use DoD class/subclass supply codes.

The intent of this thesis is to devise a method of analyzing historical data for Navy surface ships by fitting a mixture of probability distributions to this data. The use of these distributions should provide accurate consumption and sustainment rates for these ships. Included in these results will be the expected values and variances of the respective sustainment rates. From these distributions, notional ARGs and CVBGs can be assembled

for planning purposes, and the sustainment rates aggregated for the entire BG.

This thesis will be narrowed in scope to model only the consumption rates for the seven subclasses of Class IX, Repair Parts. It will also be limited to four classes of ships that might compromise a typical CVBG. These ship types include:

- CVN-68 (Nimitz Class) Aircraft Carrier,
- CG-47 (Ticonderoga Class) Guided Missile Cruiser,
- DD-963 (Spruance Class) Destroyer,
- FFG-7 (Oliver Hazard Perry Class) Guided Missile Frigate.

Newer classes of ships (such as DDG-51 Guided Missile Destroyers) were not included due to lack of data, and several older classes of ships (such as FF-1052, CG-16 and DDG-2) were excluded, despite a wealth of existing data, because they are being decommissioned.

IV. DATA COLLECTION AND ANALYSIS

The data used to model the consumption rates of repair parts for this thesis was provided by SPCC Mechanicsburg, PA. SPCC is one of the two Inventory Control Points (ICPs) within the Navy Supply System, and it is responsible for managing all non-aviation related items in the Navy's inventory. The data consisted of all surface ship requisitions from 1 January 1992 (Julian date 2001) to 29 September 1994 (Julian date 4272). There were a total of 7,020,303 requisitions.

Additional information provided by SPCC was weight and cube data on items in both the Navy and DLA supply systems. The records in these fields are listed by NIIN. There are 469,361 records in the Navy file and 3,533,161 records in the DLA file.

A. DATA MANIPULATION

The data files provided were stored on 6250 bpi (bits per inch) magnetic tapes in fixed block format. For this reason, plus the sheer magnitude of data, the files were loaded onto the Naval Postgraduate School (NPS) mainframe computer. All of the data manipulation that follows in this section was performed with SAS code or in VM/CMS with the assistance of consultants at the NPS computer center.

The first step in manipulating the data into usable format was eliminating requisitions from all ship types except the four classes of ships previously mentioned. This process actually involved several steps, the first of which was determining the desired UTCs from the TUCHA. The second step was to find the Unit Identification Codes (UICs) of the individual ships within the desired UTCs. This was accomplished using a UTC to UIC conversion Table

also provided by SPCC. Appendix A lists the four desired UTCs and their respective UICs.

Code was then written in SAS to sort through all of the requisitions, eliminating those with undesired UICs. From the requisitions that remained, only the following fields were saved (the number in parentheses represents the number of characters in that field): NIIN (9), UIC (5), Julian date of requisition (4), quantity ordered (5), FSG (2), COG (2), and a deployment indicator (1). The FSG and COG are supply codes that provide additional information about the items in the supply system, such as the manager of that item. The reason for copying these fields will be discussed later. The deployment indicator is a binary character, with a one being used if the unit submitting the requisition was deployed, zero otherwise. As a result of eliminating requisitions from ship types that we are not modeling, the following numbers of requisitions remained: 358,918 (CVN-68); 276,386 (FFG-7); 247,816 (DD-963); and 213,615 (CG-47).

The next major step involved assigning a weight to each of the requisitions. However, after combining the DLA and Navy weight files and eliminating duplicate entries, approximately 40% of the 3,606,482 unique records did not have weights assigned. It was necessary to devise a policy for adjusting to this lacuna. Merely calculating the average of all the records and using this value in place of all the missing weights was ruled out because this would significantly alter the resulting distributions and lead to underestimation of the variance. Rather, the records were broken into two categories, those with weights and those without. Random sampling (without replacement) was performed from the list of NIINs that had recorded weights, and these random values were inserted into a field called weight. This method of sampling generated a random permutation of weights which was used serially

whenever a weight was needed. In this way, the same part could have different weights assigned in subsequent draws. Otherwise, the correct weight of the item being requisitioned was inserted into this field.

In an effort to reduce the amount of random sampling required, as well as improving the accuracy of the sampling, we limited our random draws to only NIINs that had been requisitioned during the three year period. This approach prevents the chance that an extremely heavy item carried by DLA for another service could have its weight inserted into a Navy requisition. This technique, plus the previously discussed method of sampling each time we came across a NIIN without a weight, was deemed the best way to minimize distortion of the original data. Out of the 1,096,735 requisitions, there were only 174,225 unique NIINs requisitioned. From these unique NIINs, there were 135,970 (78%) that had weights assigned, while only 38,255 (22%) had missing values. Each occasion where a requisition occurred with a NIIN that had a weight of zero, a random sampling from the list with weights inserted a value into the weight field of that requisition.

Table 3 shows the results of the above procedure for each of the four ship types:

Ship type	Number of requisitions	Observations with weight	% Obs. with weight	Observations w/out weight	% Obs. w/out weight
CG-47	213,615	194,521	91.1	19,094	8.9
DD-963	247,816	232,248	93.7	15,568	6.3
FFG-7	276,386	259,280	93.8	17,106	6.2
CVN-68	358,918	304,458	84.8	54,460	15.2

Table 3. Results of Random Assignment of Weights to NIINs with Missing Values.

The results achieved by using this methodology are significantly better than using the average

values of all 3.5 million items (40% of which do not have values). For each requisition, the fields of quantity and weight were multiplied together to achieve a total requisition weight.

The third major step also involved a very subjective methodology that is worth describing in detail because it too forms an underlying assumption for the entire model. This step sorted through each of the requisitions (for each of the UTCs) and discarded those that did not belong to Class IX (Repair Parts). Those requisitions identified as being from Class IX were broken down into one of the seven subclasses listed in Table 2. These procedures utilized a table which converted the FSG and COG into a corresponding DoD supply class. This table is included as Table 4. This Table is subjective in that every item in a FSG/COG grouping is assigned to the same DoD supply class. This is not what the FSG/COG codes were designed for, so individual items may wind up being assigned to a subclass to which they do not belong. However, this method does allow generalized groupings of supply items into class/subclasses, allowing the Navy to comply with Joint Staff directives.

FSG	**COG**	**DoD Supply Class**
15,16,17	1R,3R,7R,9	9A
20	1,3H,7	9B
28,29,30,31,41,43,47,48	ALL	9B
22,25	1,3H,7	9D
59,60	ALL	9G
58,61,66	ODD	9G
14	1,3H,7	9L
10,12	1,3H,7	9M
50	1,3H,7	9T

FSG	COG	DoD Supply Class
44,46,51,52,93,94,95,96	ALL	9T
49	ODD	9T

Table 4. Guidelines for Assigning Repair Parts to DoD Supply Classes.

The data was now broken down into 28 separate files (four UTCs, seven subclasses of repair parts per UTC). Within each of these files, the weights from multiple requisitions by the same unit on the same date were added, resulting in a single value. The final step in preparing the data for analysis was to use a spreadsheet to edit out days of requisitions from units that were not deployed. This was also a fairly subjective step, because different ships reported differently as to whether they were deployed or not. For instance, several ships considered five day underway periods as deployed, and a few ships reported themselves as deployed for 1000 consecutive days. Other interpretations of whether or not a unit was deployed were involved in this step, but consistency was used throughout. After this was accomplished, the probability that an item from each subclass of Class IX was calculated for each of the four UTCs. These results, along with breakdowns of the percentages of requisitions involving actual weights versus sampled weights is included as Appendix C.

B. DATA ANALYSIS

The original intent of this thesis was to fit a single probability distribution to the weights of the daily requisitions in each subclass of repair parts. A mixed distribution would result, with a probability p_1 of having no requisitions on a given day (hence zero pounds being requisitioned), and another probability p_2 of a requisition occurring on that day. The weight of that requisition would be described by the probability distribution that best fit that set of

data. The resulting expected daily requisition weight (for a given subclass of repair part and ship type) would be computed:

$$E[weight] = \left(p_1 \times 0\right) + \left(p_2 \times \int_0^{\infty} x f(x)\, dx\right) \qquad \textbf{[1]}$$

where f(x) represents the probability density of the daily positive requisition weight. In addition to the calculating this expected value, we could also calculate its variance.

From the beginning of the study, it became apparent that this approach was not appropriate for Class IX(D), administrative vehicles. Regardless of ship type, the number of requisitions for this type of repair part are so low (a maximum of 12 requisitions during a three year period) that it was decided to model this subclass using weighted averages. Equation 21 in Chapter V illustrates the modifications to Equation 1 to arrive at an estimate for this subclass. However, Equation 1 could be not be applied directly to most of the other data files either (exceptions being Class IX(L) for FFG-7 and DD-963 ship types). The reason this simple model will not work for the other data sets is due to difficulties in fitting. The Weibull values are polarized because it is impossible to adequately fit a distribution to them. This is due to the fact that most of the daily requisition weights in any subclass for any of the four ship types were very light (ten pounds or less). On the other hand, there exist extreme cases of requisitions whose weight exceeds 100,000 pounds in almost every data set. Moreover, these outliers are from real requisitions which, far more often than not, are from actual weights and not the randomly sampled weights substituted for the NIINs listing weights of zero.

Figures 3 and 4 on the following page illustrate how these extreme weights prevent

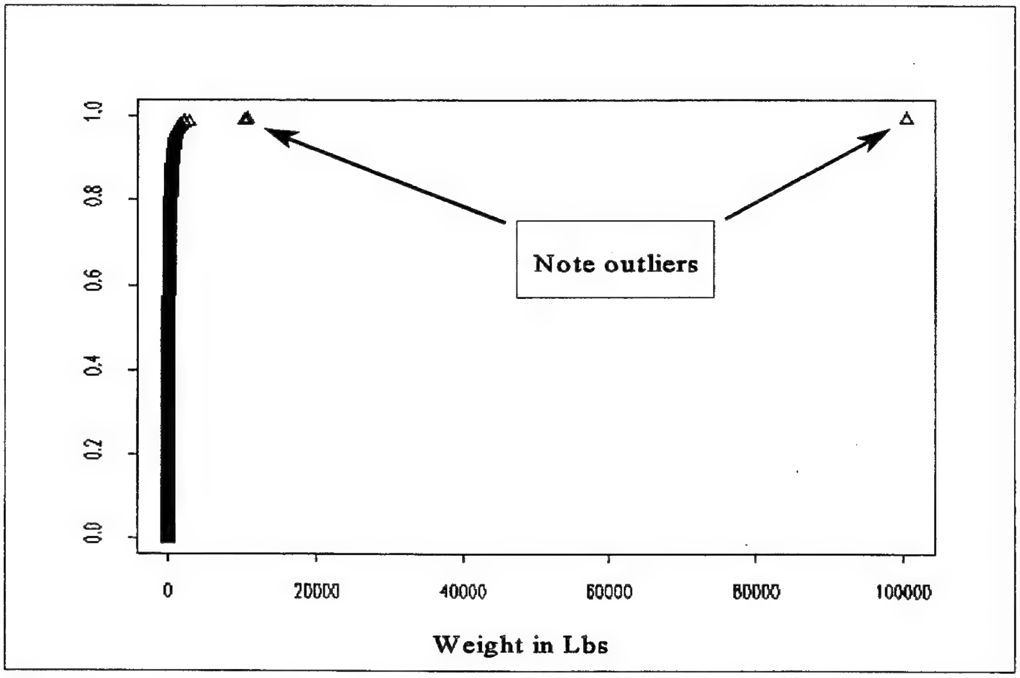

Figure 3. Empirical CDF for CVN-68 Aircraft Carrier, Class IX(A)

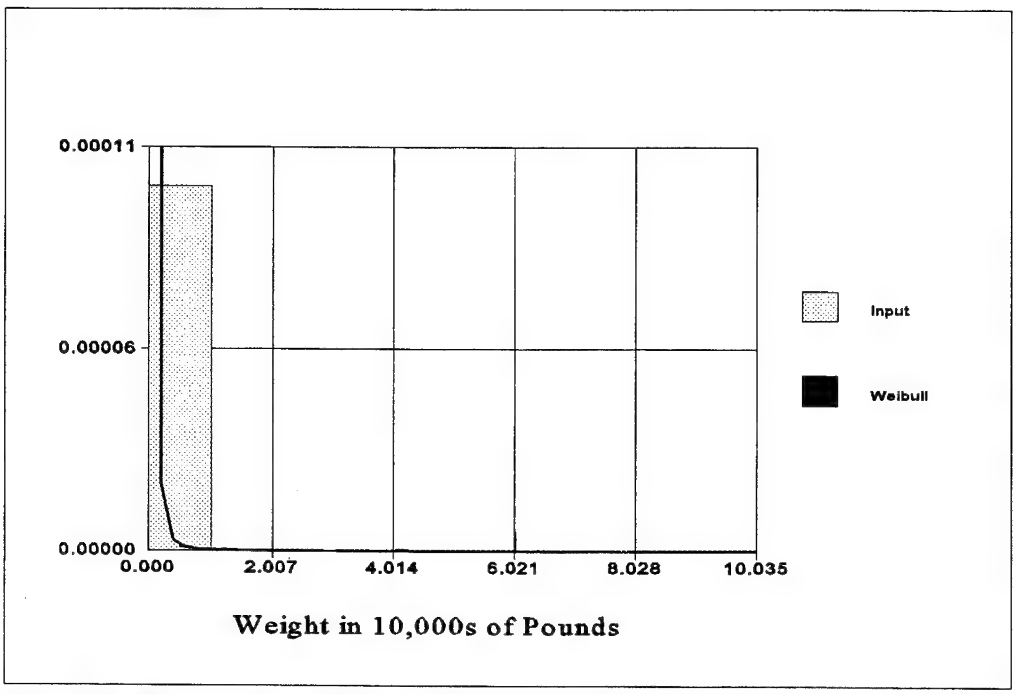

Figure 4. Histogram of CVN-68 Class IX(A) Data and Weibull(.47, 114)

any good fit of a distribution to the data. The data in the figures is from CVN-68 (aircraft carriers), Class IX(A), and it is representative of most of the data sets. Figure 3 is a plot of the empirical cumulative distribution function (ECDF) of the daily requisition weights, while Figure 4 shows a histogram of the same data and an attempt to fit a Weibull distribution to that histogram. The extreme weights force most of the data into the first class, or 'bin', of the histogram, preventing a good fit. Attempting ad hoc adjustments with the number of classes in the histogram did nothing to relieve this problem.

1. Extreme-Value Distribution

The method chosen to handle the cases of the outliers is that of modeling them using one of the extreme-value distributions for maximums. Since weights are positive, the extreme-value distribution function chosen for our data sets is the Type II, or Cauchy type, which is defined as:

$$G(y) = \exp(-y^{-\gamma}) \qquad \text{for } y>0,\ \gamma>0. \qquad \textbf{[2]}$$

This form is derived as the limiting distribution of a normalized set of maxima $Y(n) = \dfrac{X_{n:n} - b_n}{a_n}$ [Ref 14]. This type is best suited for maximums from densities having thick tails, such as the extreme values in the data sets of the requisition weights.

If these very heavy (and rare) requisitions can be modeled using an appropriate distribution, the resulting daily expected requisition weight becomes the mixture:

$$E[weight] = (p_1 \times 0) + (p_2 \times \mu_2) + (p_3 \times \mu_3) \qquad \textbf{[3]}$$

where μ_2 is the expected value of the "outlier free" portion of data, and μ_3 is the mean of

those observations in the extreme.[1] The values p_1, p_2 and p_3 are the mixing probabilities, and are defined as: p_1 for the days without requisitions, p_2 for the requisition weights not containing any outliers, and p_3 for requisitions of extreme weights.

Figures 5 and 6 on the following two pages illustrate the effects of removing the extreme values from the data set representing CVN-68 ships, Class IX(A). After truncation of the 19 heaviest requisitions (which will be modeled with the extreme-value distribution), the remaining data yields a smoother ECDF and a histogram which appears better suited for being fit by a common probability distribution.

2. Weibull Distribution

A method was devised to identify the extreme values for all of the data sets except those for Class IX(D) (all ship types) and Class IX(L) (FFG-7 and DD-963 ship types only). The extreme points were removed following this procedure, and after this truncation, the resulting ECDFs appear to resemble that of a Weibull distribution. Weibull distributions are 'J'-shaped, and provide a richer set of models than the Exponential type. They are often used in probability when attempting to model the time required to complete a task or the time to failure of a piece of equipment [Ref 15]. The data in the tail of the remaining requisitions was another factor in the selection of the Weibull distribution.

The Weibull distribution describes a continuous random variable X with two parameters: θ and β. The range for both of these parameters is $\theta,\beta > 0$. The probability

[1] The use of the Type II extreme-value distribution does not contribute a finite μ_3 for Equation 3, but we shall devise a method of dealing with this issue later.

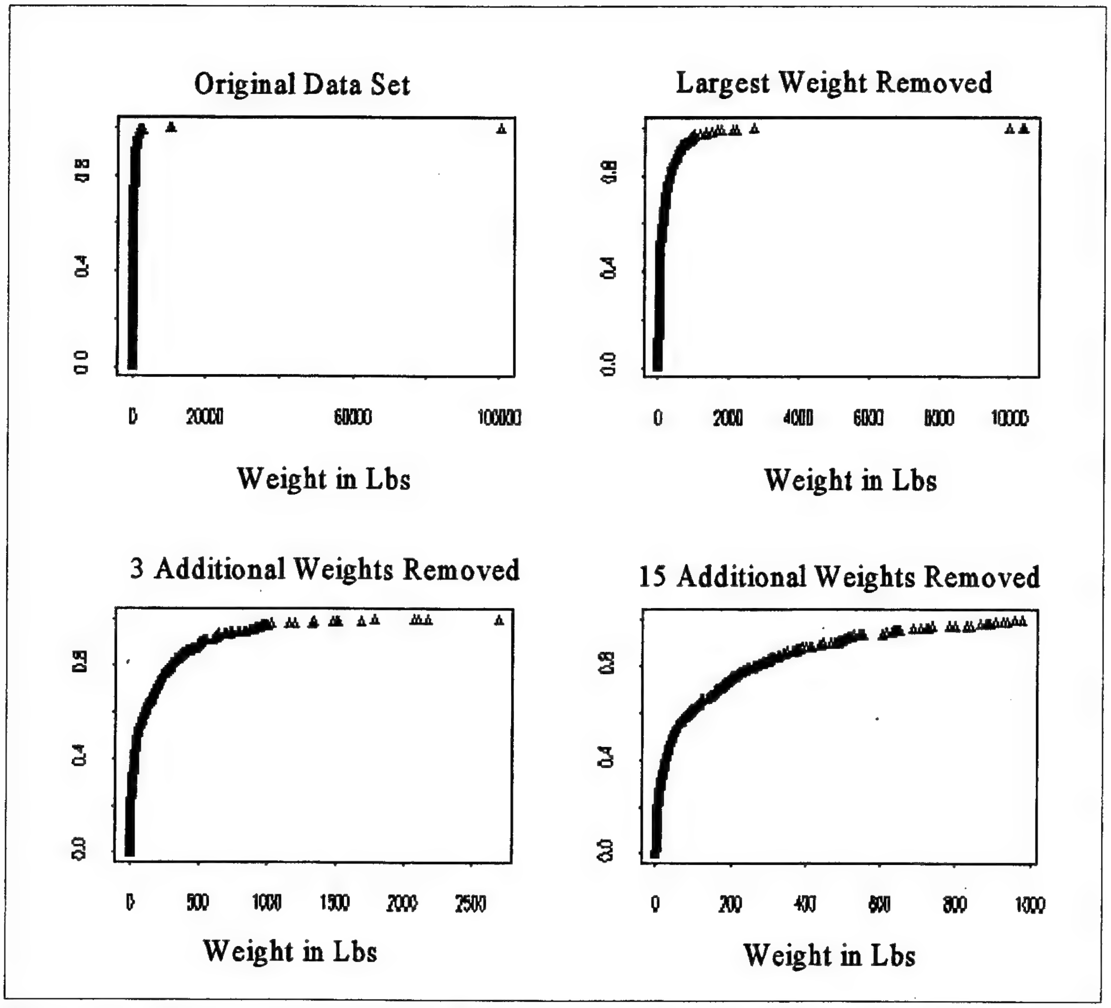

Figure 5. Empirical Cumulative Distribution Functions (ECDFs) of data sets for CVN-68, Class IX(A), as extreme values are removed. Y-Axis represents cumulative probabilities. Note changes in the ranges of the axes.

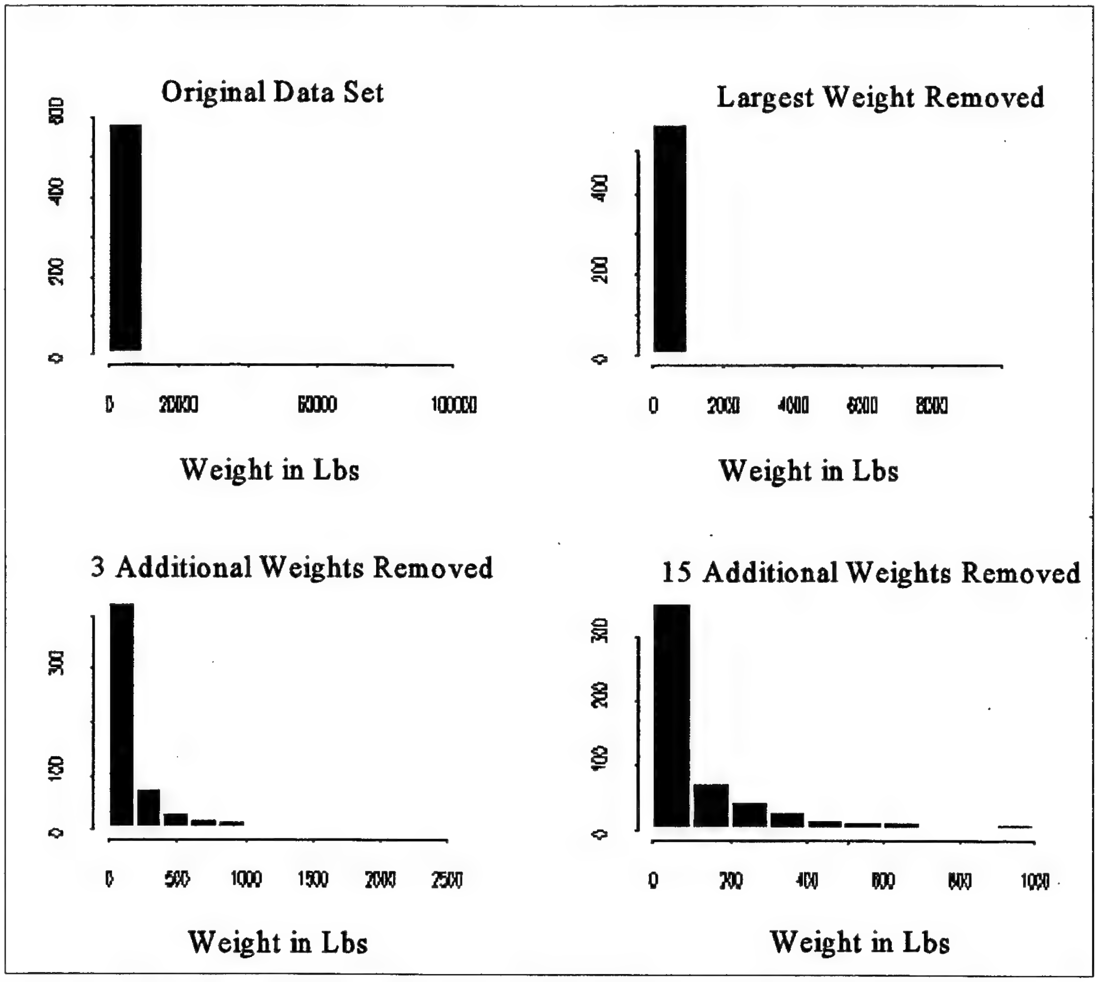

Figure 6. Histograms of data sets for CVN-68, Class IX(A), as extreme values are removed. Y-axis represents number of observations. Note changes in the ranges of the axes.

density function (pdf) for a Weibull distribution is of the form:

$$f(x;\theta,\beta) = \begin{Bmatrix} \left(\dfrac{\beta}{\theta^{\beta}}\right) x^{\beta-1} e^{-\left(\frac{x}{\theta}\right)^{\beta}} & if\ x>0 \\ 0 & otherwise \end{Bmatrix} \qquad \textbf{[4]}$$

The parameter β is called the shape parameter, while θ is the scale parameter. The Cumulative Distribution Function (CDF) of a Weibull distribution is:

$$F(x;\theta,\beta) = 1 - e^{-\left(\frac{x}{\theta}\right)^{\beta}} \qquad for\ x>0 \qquad \textbf{[5]}$$

The parameters θ and β for the Weibull distributions will be estimated using the method of maximum likelihood. The likelihood function can be described as "giving the probability of observing the data as a function of the parameters. The Maximum Likelihood Estimate (MLE) of a set of parameters is that value of the set that maximizes the likelihood - that is, makes the observed data 'most probable' or 'most likely' " [Ref 16]. The derivation of the MLEs for the Weibull follows over the next few pages.

Recall the density function for a Weibull distribution from Equation 4. Let the n values from any given data set be $x_1, x_2, \ldots, x_n$. Assuming that $x_1, \ldots, x_n$ are independent and identically distributed according to a Weibull(θ, β) distribution, then their joint density is the product of their marginal densities:

$$f(x_1,x_2,\ldots,x_n \mid \theta,\beta) = \prod_{i=1}^{n} \left[\frac{\beta}{\theta^{\beta}}\, x_i^{\beta-1} e^{-\left(\frac{x_i}{\theta}\right)^{\beta}}\right] \qquad \textbf{[6]}$$

The likelihood function (L), when regarded as a function of θ and β, is:

$$L(\theta,\beta) = \frac{\beta^n}{\theta^{n\beta}} \left[\prod_{i=1}^{n} x_i\right]^{\beta-1} e^{-\sum_{i=1}^{n}\left(\frac{x_i}{\theta}\right)^{\beta}} \qquad \textbf{[7]}$$

The log likelihood function LL = ln[L(θ,β)], is:

$$LL = n\ln(\beta) - n\beta\ln\theta) + (\beta-1)\sum_{i=1}^{n}\ln(x_i) - \sum_{i=1}^{n}\left(\frac{x_i}{\theta}\right)^{\beta} \qquad \textbf{[8]}$$

The partial derivatives of LL, with respect to the parameters θ and β, are:

$$\frac{\partial LL}{\partial\theta} = \frac{-n\beta}{\theta} - \left\{\sum_{i=1}^{n}\beta\left(\frac{x_i}{\theta}\right)^{\beta-1}\right\}(-1)\frac{x_i}{\theta^2} \qquad \textbf{[9a]}$$

$$\frac{\partial LL}{\partial\theta} = \frac{n}{\beta} - n\ln(\theta) + \sum_{i=1}^{n}\ln(x_i) - \left\{\sum_{i=1}^{n}\left(\frac{x_i}{\theta}\right)^{\beta}\right\}\ln\left(\frac{x_i}{\theta}\right) \qquad \textbf{[9b]}$$

Equations 9a and 9b are set equal to zero, and after some algebra, yield:

$$\theta^{\beta} = \frac{\sum_{i=1}^{n} x_i^{\beta}}{n} \qquad \textbf{[10a]}$$

$$\frac{1}{\beta} = \frac{\sum_{i=1}^{n} x_i^{\beta}\ln(x_i)}{\sum_{i=1}^{n} x_i^{\beta}} - \frac{\sum_{i=1}^{n}\ln(x_i)}{n} \qquad \textbf{[10b]}$$

The first parameter we solve for is β. We do this by defining g(β), where:

$$g(\beta) = \frac{\sum_{i=1}^{n} x_i^{\beta}\ln(x_i)}{\sum_{i=1}^{n} x_i^{\beta}} - \frac{1}{\beta} \qquad \textbf{[11]}$$

An iterative process (Newton's Method) is now used to solve for β:

$$\beta_1 = \beta_0 - g(\beta) - \frac{\sum_{i=1}^{n} \ln(x_i)}{g'(\beta)} \qquad [12]$$

where $g'(\beta)$ is the derivative of $g(\beta)$:

$$g'(\beta) = \frac{\left(\sum_{i=1}^{n} x_i^{\beta}\right)\left[\sum_{i=1}^{n} x_i^{\beta}\ln(x_i)^2\right] - \left[\sum_{i=1}^{n} x_i^{\beta}\ln(x_i)\right]^2}{\left[\sum_{i=1}^{n} x_i^{\beta}\right]^2} \qquad [13]$$

β_0 is initially set equal to 1, and replaced by $\beta 1$ at each iteration, and the process of updating β_1 continues until $|\beta_1 - \beta_0| < \epsilon$, where ϵ is a very small number (we use 0.001). Once the value of β has been determined using this method, the value of θ can be calculated using Equation 10a.

Having calculated these estimates, their values will be inserted in the following equations to get summary statistics. The mean (E[X]) and variance (Var[X]) can be determined from the formulas:

$$E(X) = \theta\Gamma\left(1 + \frac{1}{\beta}\right) \qquad [14]$$

$$Var(X) = \theta^2\left[\Gamma\left(1 + \frac{2}{\beta}\right) - \Gamma^2\left(1 + \frac{1}{\beta}\right)\right] \qquad [15]$$

where $\Gamma(x)$ denotes the gamma function, which is defined for all real x>0 by:

$$\Gamma(x) = \int_0^\infty t^{x-1} e^{-t} dt \qquad [16]$$

Finally, the $100 \times p^{\text{th}}$ percentile of a Weibull distribution is of the form:

$$X_p = \theta\left[-\ln(1-p)\right]^{\frac{1}{\beta}} \qquad [17a]$$

We will also be working with the median value of these Weibull distributions, which is defined as the 50th percentile (or $X_p = .5$). This special form of Equation 17a is:

$$X_{(.5)} = \theta\left[-\ln(.5)\right]^{\frac{1}{\beta}} \qquad [17b]$$

3. Methodology for Determining Extreme Values

We wanted to develop a standard methodology for identifying extreme weights which could be used on all of the data sets, rather than using subjective guesswork. Such a universal standard has eluded us, nor was it possible to identify a single weight as *the* cutoff between regular and extreme. However, we were able to establish rough "rule of thumb" guidelines that enabled us to set criteria which could generally be applied to a given subclass of repair parts (across all ship types).

The first step in this process involved calculating the ratio of the empirical mean and median values from a given data set. These are compared with the same ratio using the

theoretical mean and median values. Such ratios provide information about the skewness of the underlying data sets. Upon completion of this step, the largest (i.e., heaviest) item in the data set is removed, and the calculations repeated until we get a reasonable match between the two. The idea here is to remove outliers until the empirical ratio of mean to median agrees with the theoretical. This process generally repeats around 50 times; the actual counts ranging from 11 to 85. Operationally, the ratios of actual mean to actual median and theoretical mean to theoretical median are simultaneously plotted against the percentage of requisitions being truncated. Figure 7 on the following page illustrates the results of these plots for Class IX(G) repair parts for all four classes of ship.

Our original intentions were to examine these plots and identify obvious "knees" in the curves of the empirical skewness (i.e., when the ratio of mean to median stopped dropping off sharply as additional weights are truncated). These knees in the curve would serve as appropriate places to stop truncating requisition weights as extreme. This method only worked in a few cases, so we retreated to the method of the previous paragraph. The intersection points are not sharply determined, but approximate solutions seem serviceable. This approach worked well for some of the subclasses (such as IX(G) in Figure 7), but not in all of them. In several cases the plots of the ratios behaved very unpredictably.

We then sought ways of developing criteria allowing for the truncation of extreme points from the other data sets. In doing so, we developed the following rough guidelines:

- As the actual ratio of mean to median decreases to approximately 2.5, the behavior of the skewness curves starts to behave unpredictably. The reason for this is mainly due to the fact that the values being truncated are no longer extreme. This type of activity is depicted in Figure 8 on page 38:

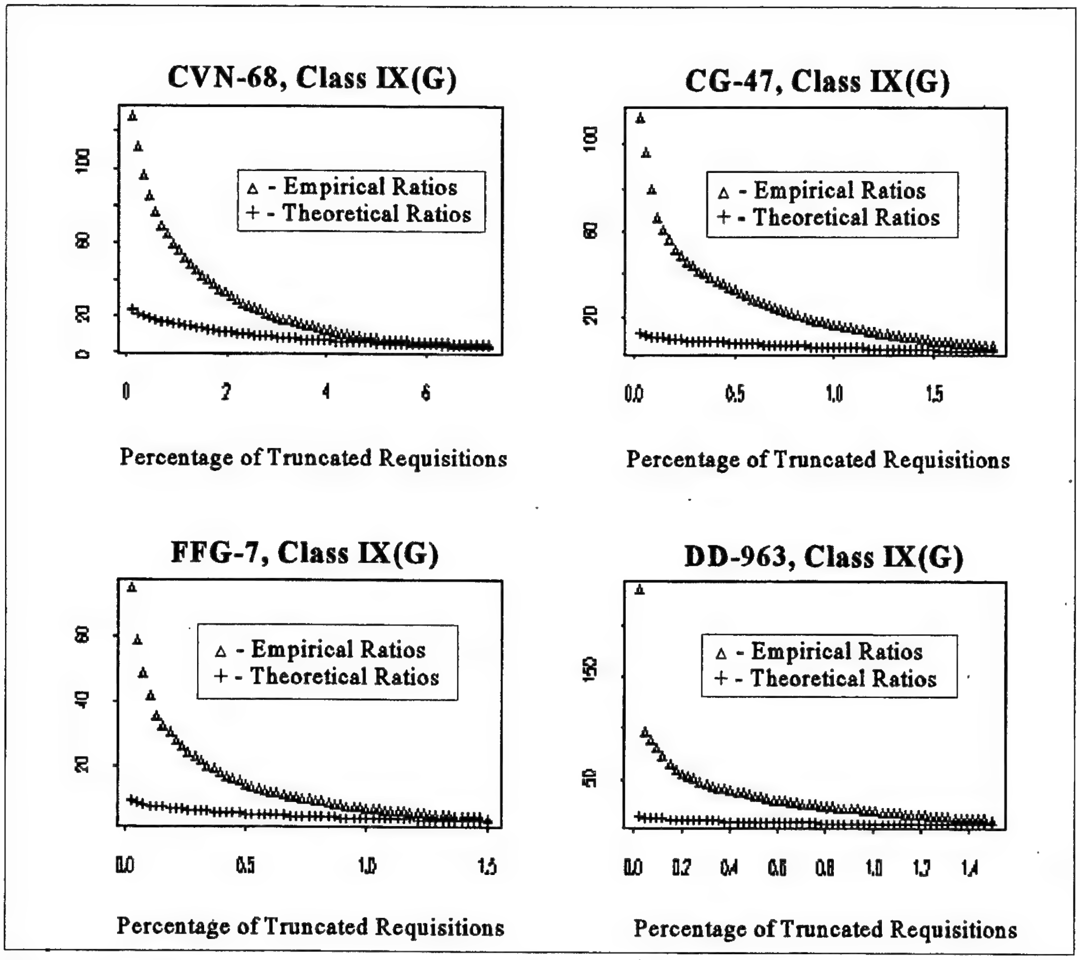

Figure 7. Plots of actual and theoretical ratios of mean to median against percentage of truncated requisitions. Class IX(G) is plotted for all ship types.

- For the larger data sets (Classes IX(B), IX(G), IX(T)), do not truncate more than 5% of the weights as extreme. The remaining data sets (Classes IX(A), IX(L), IX(M)) should not be truncated beyond 13% of the weights.

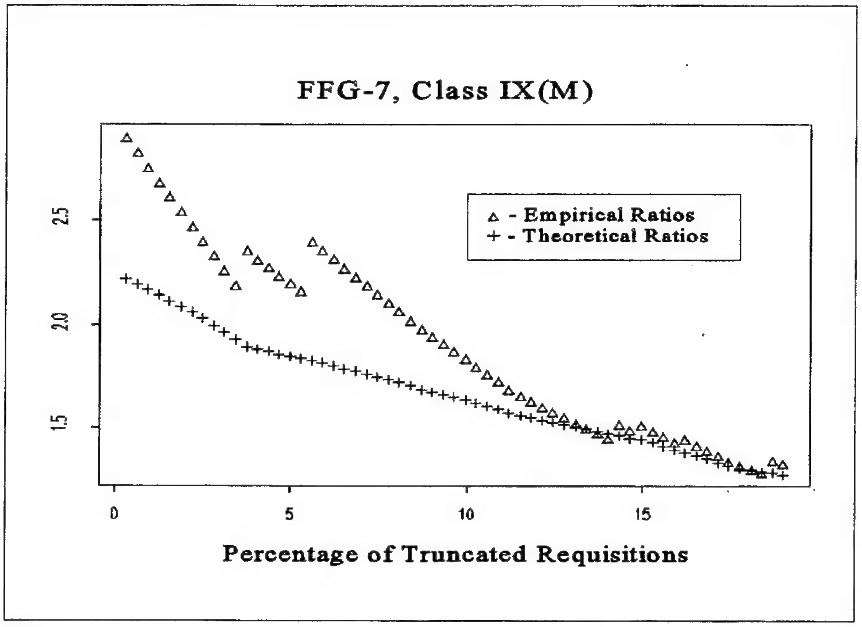

Figure 8. Illustration of Low Ratios Between Mean to Median Values.

- Calculate the ratio of the actual (mean to median) ratio over the theoretical (mean to median) ratio. Continue truncating weights as long as this value is greater than 2.2. Further truncation will probably be required, but this serves as a good upper bound.

- Lastly, observe the values of the Kolmogorov-Smirnov statistics as additional weights are truncated to see if a better fit of a distribution to the data can be achieved by further truncations. A discussion of this statistic follows in the next section.

These guidelines should not serve as rigid rules to be followed for all circumstances. Rather, they serve as steps to point future analysis in the right direction.

4. Kolmogorov-Smirnov Statistic

The Kolmogorov-Smirnov (K-S) statistic measures the goodness of fit of a hypothesized CDF to a given sample ECDF. In other words, the K-S test evaluates how well our Weibull(θ,β) distributions fit the ECDFs of the data sets. It accomplishes this by determining the maximum difference between the sample ECDF (the requisition data) and the hypothesized CDF (the Weibull distribution) [Ref 14]. The K-S distance function (D_n) is defined for a given H_0: X~F(X) as follows:

$$D_n^+ = \max_{1 \leq i \leq n} \left\{ \frac{i}{n} - F\left(X_{(i)}\right) \right\} \qquad \textbf{[18a]}$$

$$D_n^- = \max_{1 \leq i \leq n} \left\{ F\left(X_{(i)}\right) - \frac{(i-1)}{n} \right\} \qquad \textbf{[18b]}$$

$$D_n = \max\left\{ D^+, D^- \right\} \qquad \textbf{[18c]}$$

where $X_{(1)}$, $X_{(2)}$, ... , $X_{(n)}$ are the n order statistics from the data set, i is an index from 1 to n, and F(X) is our hypothesized distribution.

The result of the K-S test is the distance function D_n, and small values indicate better fits. "The test rejects the null hypothesis (H_0) if D_n exceeds some constant $d_{n,\,1-\alpha}$, where α is the specified level of the test" [Ref 15]. Our calculations used a value of α=.05. The K-S test was selected over other more common tests (such as the chi-square test) because it is easier to use on large sample sizes and it uses ungrouped data, so the goodness of fit is measured at every data point. It also prevents the necessity of having to determine interval widths and

does not require a correction for continuity [Ref 17].

The K-S distance function is evaluated only on the data with positive (i.e., greater than zero) values. Recall from Equation 3:

$$p_1 = \textit{probability of no requisition on a given day}$$

$$p_2 = \textit{probability of a requisition of non-extreme weight}$$

$$p_3 = \textit{probability of a requisition of extreme weight}.$$

We next define:

$$n_2 = \textit{number of requisitions described by Weibull}$$

$$n_3 = \textit{number of requisitions described by EV function}$$

$$i = 1,\ 2,\ \ldots,\ n_2 + n_3$$

$$p_2' = \frac{p_2}{1 - p_1}$$

$$p_3' = \frac{p_3}{1 - p_1},$$

and let $X_{(1)}, X_{(2)}, \ldots, X_{(n2+n3)}$ be the ordered weights of the requisitions in any given data set, where $X_{(1)} \le X_{(2)} \le \ldots \le X_{(n2+n3)}$. We further define F(X) as the Weibull distribution and G(X) as the EV distribution. Now we calculate $F_0(X_{(i)})$ for all i = 1, 2, ... , n_2+n_3, where $F_0(X_{(i)})$ is defined as:

$$F_0(X_{(i)}) = \left\{p_2' \times F(X_{(i)})\right\} + \left\{p_3' \times G(X_{(i)})\right\} \qquad \textbf{[19]}$$

The value of $F_0(X_{(i)})$ is used in Equation 18c to obtain the K-S distance of our function.

5. Fitting Distributions to the Data

Table 5 lists the breakdown of the data into the three categories of requisitions:

Ship	Class	Days Deploy	No Req	p_1	Days ~Weib	p_2	Days ~EV	p_3
CVN	IX(A)	918	330	.359	587	.640	1	.001
CVN	IX(B)	918	193	.210	704	.767	21	.023
CVN	IX(G)	918	62	.067	793	.864	63	.069
CVN	IX(L)	918	801	.873	112	.122	5	.005
CVN	IX(M)	918	708	.771	209	.228	1	.001
CVN	IX(T)	918	356	.387	533	.581	29	.032
CG47	IX(A)	6364	6216	.977	134	.021	14	.002
CG47	IX(B)	6364	3831	.602	2523	.396	10	.002
CG47	IX(G)	6364	2957	.465	3334	.524	73	.011
CG47	IX(L)	6364	6319	.992	45	.007	1	.001
CG47	IX(M)	6364	6098	.957	265	.042	1	.001
CG47	IX(T)	6364	5209	.819	1108	.174	47	.007
FFG7	IX(A)	8407	8211	.977	178	.021	18	.002
FFG7	IX(B)	8407	5658	.673	2735	.325	14	.002
FFG7	IX(G)	8407	4608	.548	3739	.445	60	.007
FFG7	IX(L)	8407	8338	.992	69	.008	0	0
FFG7	IX(M)	8407	8086	.962	280	.033	41	.005
FFG7	IX(T)	8407	7186	.855	1172	.139	49	.006
DD	IX(A)	8344	8212	.984	120	.015	12	.001
DD	IX(B)	8344	5393	.646	2937	.352	14	.002
DD	IX(G)	8344	4382	.525	3877	.465	85	.010
DD	IX(L)	8344	8264	.990	80	.010	0	0

Ship	Class	Days Deploy	No Req	p_1	Days ~Weib	p_2	Days ~EV	p_3
DD	IX(M)	8344	7986	.957	315	.038	43	.005
DD	IX(T)	8344	7136	.855	1171	.141	37	.004

Table 5. Results of Breaking Data into Three Categories of Requisitions

No distributions are being fit to the data from Class IX(D) due to the very low numbers involved. From the remaining data sets, most have been broken down into two subsets: the 'regular' requisition weights that will be fit by a Weibull distribution, and the extreme cases, which will be handled by the EV distribution. A small number of remaining data sets will be modeled only with the Weibull distribution (i.e., p_3 is zero).

Determining the parameters for the Weibull distribution is straightforward, using the method of maximum likelihood previously discussed. The parameters of the Weibull distributions fit to the data sets are listed in Appendix C. Included in this Appendix are the old K-S distances determined prior to the truncation of extreme points, as well as the K-S distances calculated after the truncation. Except for the two instances where no truncations of extreme points occurred, the fit of a Weibull distribution to the data is better. In some cases, this improvement is quite dramatic. There is difficulty in determining the parameters for the EV distribution. Recall from Equation 2 that G(y) is the limiting distribution of a standardized $Y = \frac{X - b}{a}$, where X is the requisition weight and a,b are scaling parameters. The two parameters a and b are both unknown, as is the value for γ in Equation 2. These values will be estimated using an ad hoc technique.

The technique applied is that of adjusting the parameters a, b and γ until the Q-Q plot

(empirical versus theoretical) of the data is as close to a straight line as possible. We accomplish this by plotting v_j against u_j for each data set, where v_j and u_j are:

$$v_j = \ln\left(-\ln\left(\frac{j}{m+1}\right)\right) \qquad \textbf{[20a]}$$

$$u_j = \ln\left(X_{(j)} - b\right), \qquad \textbf{[20b]}$$

where m is the number of values in the data set; j is a vector of indices from 1 to m. Next we adjust the value of b in Equation 20b until the scatterplot forms as straight a line as possible. Simple regression is performed on this line to obtain the slope and intercept. A demonstration of this technique is provided in Appendix D. Submitted without explanation, the slope of this line is the negative value of γ. The value of a is calculated from the intercept, which is equal to $\gamma\ln(a)$. The results of this technique are also listed in Appendix D.

V. RESULTS OF ANALYSIS

A. DATA SETS TREATED AS WEIGHTED AVERAGES

The first section of this chapter deals with the very small data sets of Class IX(D). These data sets had very few requisitions, and those that did occur had relatively low weights. We will call the number in the last column the Central Value. This Central Value is calculated with only a slight modification to Equation 1:

$$E\left[\mathit{Central\ Value}\right] = (p_1 \times 0) + (p_2 \times \mu^*) \qquad \textbf{[21]}$$

where μ^* is the empirical average requisition weight from all of the requisitions in that data set. The values for this subclass are extremely low, as Table 6 illustrates:

Ship	# Days Deployed	# Days With Req's	p[Req on Given Day]	Avg Req Weight	Central Value
CVN-68	918	7	.0076	218.61	1.667
CG-47	6364	3	.0005	52.67	0.026
FFG-7	8407	12	.0014	23.22	0.033
DD-963	8344	2	.0002	110.25	0.022

Table 6. Expected Daily Requisition Weight for Class IX(D).

B. DATA SETS WITH NO EXTREME VALUES

This section discusses results of the cases where no requisition weights were truncated. These were both in Class IX(L), for FFG-7 and DD-963 ship types. The parameters of the Weibull distribution fitting those data sets are given in Table 7, as well as the resulting Central Value, which is solved using Equation 1 and the mean value of the

Weibull distribution that was fitted to the actual requisition weights. The K-S distance of the distribution fit and the rejection cutoff for the K-S test at a value of α=.05 are also included:

Ship	P[req]	θ	β	mean	var	Cent. Value	K-S dist	K-S cutoff
FFG-7	.008	9.33	.69	11.976	317.06	.096	.120	.164
DD963	.010	16.23	.73	19.772	760.08	.198	.130	.152

Table 7. Expected Daily Requisition Weights for Data Sets with No Truncation.

C. DATA SETS WITH EXTREME VALUES

This section discusses the results of most of the data sets that were modeled, and it includes data sets which include days with no requisitions, days with requisitions of items of 'regular' weight that are modeled by the Weibull distribution, and days with extreme requisition weights which are modeled by the Extreme-Value distribution. The Central Values for this section were calculated using a modification of Equation 3. The point that must be addressed is that no mean and variance exist for the Type II Limiting Distribution that we chose to use. Instead, we calculated the three quartiles of the distribution. That is, Equation 22 is used to calculate quantiles for values of p = .25, .50 and .75:

$$p = e^{(-y)^{-\gamma}} \qquad \textbf{[22]}$$

The quantile at p=.5 (or $q_{(.5)}$) is the median value that we will use, after scale change, in place of μ_3 for the purposes of calculating the Central Value. No variance exists for this distribution either, and we will calculate the Inner-Quartile Range (IQR) for use as a measure of spread. It is defined as:

$$IQR = q_{(.75)} - q_{(.25)} \qquad \textbf{[23]}$$

The IQR gives an interval of values that contains 50% of the cases. The value γ in Equation 22 comes from Table D-1 in Appendix D, and the equation is solved for y. The solution to Equation 22 must be converted to the original units for use in the Tables using Equation 24:

$$X = b + aY \qquad \textbf{[24]}$$

where the values for 'a' and 'b' come from Table D-1. Thus, $q_{(.5)}$ is converted to the "X"scale and used for μ_3.

The effect of all this is to output some hybrid measure. The choice of a central value is awkward, and requires further study. The expected value is preferable because the period total is computed as the product of expected value with days in the period. The median (or other quantile figures) does not have this very desirable property. Indeed, for many of our cases, $p_1 > 0.5$, and for these instances, the median is zero. As an expedient, we are using the Weibull mean for μ_2 and the extreme value median for μ_3. At least this latter value is finite and serves as something that can be used in computation, albeit we anticipate the result to be on the low side. With regards to variablity, one can be reminded that for normal variates the IQR is roughly 1.35 standard deviations. This conversion is of limited usefulness for heavily skewed distributions. Although the entries do not blend well, they are the best we can do under the circumstances.

The output in Table 8 on the next page illustrates the results of applying the preceding method.

A brief discussion of what the output in Table 8 represents follows:

Column 1 - The ship type and Subclass of Repair Part being modeled;

Columns 2,3,4 - The probabilities defined in Equation 3;

Column 5 - Expected Values of the Weibull distributions fitted to the data;

Column 6 - Product of p_2 and the values from Column 5;

Column 7 - Variance of values from the Weibull distributions;

Column 8 - The $q_{(.5)}$ quantile (median value) from E-V distribution;

Column 9 - Product of p_3 and the values from Column 8;

Column 10 - The IQR of the extreme weights ($q_{(.75)}$ - $q_{(.25)}$);

Class	p1	p2	p3	μ_2	p2*μ_2	Var[Weib]	q(.5)	p3*q(.5)	IQR
CV 9A	0.36	0.64	0.00	222	142.08	246420	100352	100.35	N/A
CV 9B	0.21	0.77	0.02	297.95	228.53	529868	16862.26	387.83	14709.6
CV 9G	0.07	0.86	0.07	411.82	355.81	722656	113856.5	7856.1	182010
CV 9L	0.87	0.12	0.01	16.56	2.02	324.53	210.49	1.05	251.31
CV 9M	0.77	0.23	0.00	83.08	18.94	25423	80000	80	N/A
CV 9T	0.39	0.58	0.03	227.33	132.08	375967	28417.8	909.37	73923.6
CG 9A	0.98	0.02	0.00	3.76	0.08	15.64	87.35	0.17	90.89
CG 9B	0.60	0.40	0.00	56.16	22.24	10616.6	19734.6	39.47	25439.2
CG 9G	0.47	0.52	0.01	70.08	36.72	16532.7	41773.2	459.51	69932.8
CG 9L	0.99	0.01	0.00	12.71	0.09	179.16	250	0.25	N/A
CG 9M	0.96	0.04	0.00	40.51	1.7	3397.2	390	0.39	N/A
CG 9T	0.82	0.17	0.01	26.21	4.56	1883.7	2149.9	15.05	6560.9
FFG 9A	0.98	0.02	0.00	4.7	0.1	33.28	61.18	0.12	41.08
FFG 9B	0.67	0.33	0.00	54.57	17.74	12687	15786.4	31.57	17916.5
FFG 9G	0.55	0.45	0.01	47.15	20.98	6872.2	42916.3	300.41	67894.1
FFG 9M	0.96	0.03	0.01	12.11	0.4	162.5	118.79	0.59	63.16
FFG 9T	0.86	0.14	0.01	22.6	3.14	1578.48	642.61	3.86	1338.93
DD 9A	0.98	0.02	0.00	4.52	0.07	24.72	75.68	0.08	59.49
DD 9B	0.65	0.35	0.00	55.61	19.57	10409.25	7495.3	14.99	6910.9
DD 9G	0.53	0.47	0.01	64.13	29.82	15880	43413	434.13	47709.3
DD 9M	0.96	0.04	0.01	14.02	0.53	249.12	132.21	0.66	105.7
DD 9T	0.86	0.14	0.00	26.95	3.8	2444.1	958.8	3.84	2215.04

Table 8. Parameters for Use With Mixed Distributions.

D. COMPARISON OF OLD LFF CONSUMPTION RATES AND NEW RATES

Table 9 below illustrates the significant differences that exist between the old factors and the new factors calculated using the mixed distribution methodology developed in this study:

Subclass	Current CVN-68 Factor	New CVN-68 Factor	Current CG-47 Factor	New CG-47 Factor	Current FFG-7 Factor	New FFG-7 Factor	Current DD-963 Factor	New DD-963 Factor
IX(A)	326.00	242.43	1.00	0.25	0.00	0.22	0.00	0.14
IX(B)	78.00	616.36	7.00	61.71	1.00	49.31	7.00	34.57
IX(D)	3.00	1.67	1.00	0.03	0.00	0.03	0.00	0.02
IX(G)	234.00	8211.91	19.00	496.23	8.00	321.40	23.00	463.95
IX(K)	59.00	N/A	6.00	N/A	3.00	N/A	4.00	N/A
IX(L)	16.00	3.07	0.00	0.34	0.00	0.16	0.00	0.15
IX(M)	6.00	98.94	0.00	2.09	0.00	0.99	0.00	1.19
IX(T)	623.00	1041.45	37.00	19.61	9.00	7.00	17.00	7.64
TOTAL	1345.00	10,215.8	71.00	580.26	21.00	379.11	51.00	507.66

Table 9. Comparison of Current Factors in Navy LFF To New Factors Derived from Recent Historical Data and Mixed Probability Distributions.

This table demonstrates that the current factors are generally low by a factor of ten. This could mean that existing OPLANs are deficient in estimating sustainment requirements for a CVBG by the same factor of ten, which calls into question any logistics feasibility analysis that has been performed on those OPLANs.

VI. CONCLUSIONS

It is the conclusion of this thesis that the Navy's LFF is grossly out of date. Using available historical data, we have justified a rough rule that the current consumption factors in the LFF are "low by an order of magnitude", at least in the case of Class IX, Repair Parts. This conclusion is underscored by the fact that the data was collected during "peacetime" deployments. The operational tempo of these deployments may have been high, but the ships were not attacked by the enemy. Logic dictates that once battle damage occurs, the requests for repair parts will only increase.

A significant amount of data massaging was required by this study. Several ad hoc techniques were necessary because of the condition of the data. While we submit that these breaches of pure statistical analysis were carried through the analysis to the results, at least in form, they cannot explain the order of magnitude difference between the old and new sets of factors. However, unlike the current factors, we developed and clearly documented our methodology. As a result, future analysts in this area can use all, part or none of our methodology, because they will know what we did to arrive at our results.

The Navy is moving to comply with all aspects of the directives issued by the Joint Staff regarding the improvement and maintenance of the LFF. One of the most significant results of the work done by PRC, Inc., was to identify specific organizations to be responsible for maintaining the factors current for individual subclasses of supply. Additionally, a single person has been established as a point of contact at each of the cognizant agencies. The results of these steps should make for easier and more efficient maintenance of the LFF.

The requisition data that was provided by SPCC for this study was complete and thorough. We feel strongly that historical data such as this is the best way to model and predict future consumption factors. However, weight and cube (volume) data must be accurate to successfully model the consumption factor as a function of weight. We recommend that any further studies in this area begin by cleaning up this data. Once this has been done, it can be followed by a more studied and carefully structured approach to the model fitting.

APPENDIX A. UNIT TYPE CODES AND UNIT IDENTIFICATION CODES

This appendix lists the UTCs of the four ship classes being modeled, as well as the UICs of the ships belonging to that UTC:

UTC 5CVN1 (8 CVN-68 Nimitz Class Aircraft Carriers)

03368	20993	21297	21847
03369	21247	21412	21853

UTC 5DDD3 (31 DD-963 Spruance Class Destroyers)

20574	20591	20611	20834	20589
20575	20598	20612	20835	20590
20576	20599	20613	20836	20603
20586	20600	20614	20837	30604
20587	20601	20615	20838	20617
20588	20602	20616	20839	20833
21416				

UTC 5GEG1 (52 FFG-7 Oliver Hazard Perry Class Frigates)

21028	20975	21103	21231	20973
21032	20976	21104	21232	20974
21033	20977	21105	21233	21058
21034	20978	21106	21234	21059
20964	20979	21107	21235	21200
20965	21052	21108	21236	21201
20966	21053	21109	21350	21430
20967	21054	21110	21351	21111
20968	21055	21197	21352	
20969	21056	21198	21390	
20972	21057	21199	21391	

UTC 5JCG2 (27 Ticonderoga Class Aegis Cruisers)

21281	21387	21450	21658	21346
21225	21388	21451	21684	21449
21295	21389	21623	21827	21657
21296	21428	21624	21828	
21344	21429	21625	21829	
21345	21447	21656	21830	

APPENDIX B. DATA MANIPULATION RESULTS

The four tables in Appendix B display the results of the data manipulation discussed in Chapter IV. They show the number of days deployed units within each of the UTCs requisitioned a repair part from each subclass. Additional information in the tables include the number of requisitions that had actual weights assigned and the total number of requisitions. From this information, the percentages of requisitions based on actual weight data is compared to the percentages of those that had random weights assigned.

Subclass	Number of days with reqs	Number of reqs w/ actual weight	Total number of reqs	Percent reqs w/actual weights	Percent reqs w/ random weights
IX(A)	588	5,200	5,622	92.5	7.5
IX(B)	725	8,882	10,162	87.4	12.6
IX(D)	7	10	10	100.0	0.0
IX(G)	856	31,157	34,594	90.1	9.9
IX(L)	117	178	179	99.4	0.6
IX(M)	210	316	320	98.8	1.2
IX(T)	562	4,997	6,089	82.1	17.9

Table B-1. Result of Data Manipulation on CVN-68 Class. 918 Deployed Days.

Subclass	Number of days with reqs	Number of reqs w/ actual weight	Number of reqs w/ random weight	Percent reqs w/actual weights	Percent reqs w/ random weights
IX(A)	148	179	199	90.0	10.0
IX(B)	2,533	10,513	11,880	88.5	11.5
IX(D)	3	3	3	100.0	0.0
IX(G)	3,407	20,004	21,795	91.8	8.2
IX(L)	45	77	77	100.0	0.0
IX(M)	266	307	316	97.2	2.8
IX(T)	1,155	3939	4288	91.7	8.3

Table B-2. Results of Data Manipulation on CG-47 Class. 6364 Deployed Days

	Number of days with reqs	Number of reqs w/ actual weight	Number of reqs w/ random weight	Percent reqs w/actual weights	Percent reqs w/ random weights
IX(A)	196	253	273	92.7	7.3
IX(B)	2,749	9,996	10,743	93.0	7.0
IX(D)	12	18	18	100.0	0.0
IX(G)	3,799	20,125	21,464	93.8	6.2
IX(L)	69	95	96	99.0	1.0
IX(M)	321	371	374	99.2	0.8
IX(T)	1,222	4,024	4,236	95.0	5.0

Table B-3. Results of Data Manipulation on FFG-7 Class. 8,407 Deployed Days.

	Number of days with reqs	Number of reqs w/ actual weight	Number of reqs w/ random weight	Percent reqs w/actual weights	Percent reqs w/ random weights
IX(A)	132	161	173	93.1	6.9
IX(B)	2,951	12,179	13,275	91.7	8.3
IX(D)	2	2	2	100.0	0.0
IX(G)	3,962	24,541	25,949	94.5	5.5
IX(L)	80	90	92	97.8	2.2
IX(M)	358	425	439	96.8	3.2
IX(T)	1,208	3,579	3,771	94.9	5.1

Table B-4. Results of Data Manipulation on DD-963 Class. 8,344 Deployed Days.

APPENDIX C. RESULTS OF FITTING WEIBULL DISTRIBUTIONS

Appendix C lists the parameters of the Weibull distributions used to fit the data sets after the truncation of extreme values. It also illustrates the improvements in this fit by listing the old K-S distance prior to truncation as well as the new K-S distance:

Ship	Class	β	θ	Old K-S Distance	New K-S Distance
CVN-68	IX(A)	.50	111	.044	.036
CVN-68	IX(B)	.47	132	.082	.072
CVN-68	IX(G)	.53	228	.148	.053
CVN-68	IX(L)	.92	15.92	.155	.127
CVN-68	IX(M)	.56	50.15	.154	.135
CVN-68	IX(T)	.44	87.13	.128	.084
CG-47	IX(A)	.95	3.67	.174	.130
CG-47	IX(B)	.58	35.66	.102	.058
CG-47	IX(G)	.58	44.50	.263	.076
CG-47	IX(L)	.95	12.42	.166	.148
CG-47	IX(M)	.71	32.43	.063	.062
CG-47	IX(T)	.63	18.51	.191	.068
FFG-7	IX(A)	.82	4.22	.137	.137
FFG-7	IX(B)	.53	30.21	.114	.080
FFG-7	IX(G)	.60	31.34	.245	.076
FFG-7	IX(L)	.69	9.33	.120	No Trunc
FFG-7	IX(M)	.95	11.83	.172	.115
FFG-7	IX(T)	.60	15.02	.148	.079

Ship	Class	β	θ	Old K-S Distance	New K-S Distance
DD-963	IX(A)	.91	4.32	.147	.117
DD-963	IX(B)	.58	35.31	.080	.056
DD-963	IX(G)	.55	37.67	.304	.086
DD-963	IX(L)	.73	16.23	.130	No Trunc
DD-963	IX(M)	.89	13.24	.137	.092
DD-963	IX(T)	.58	17.11	.126	.059

Table C-1. Results of Fitting Weibull Distributions To Data Sets

APPENDIX D. DETERMINING PARAMETERS FOR EV DISTRIBUTION

This appendix provides an example of the ad hoc technique used to determine the parameters for the EV Distribution. Figure D-1 below illustrates the effects of varying the parameter b in equation 19b to form a straight line in the scatterplot. The example shown is for FFG-7 ship type, Class IX(T). The value of b=200 yields the straightest line:

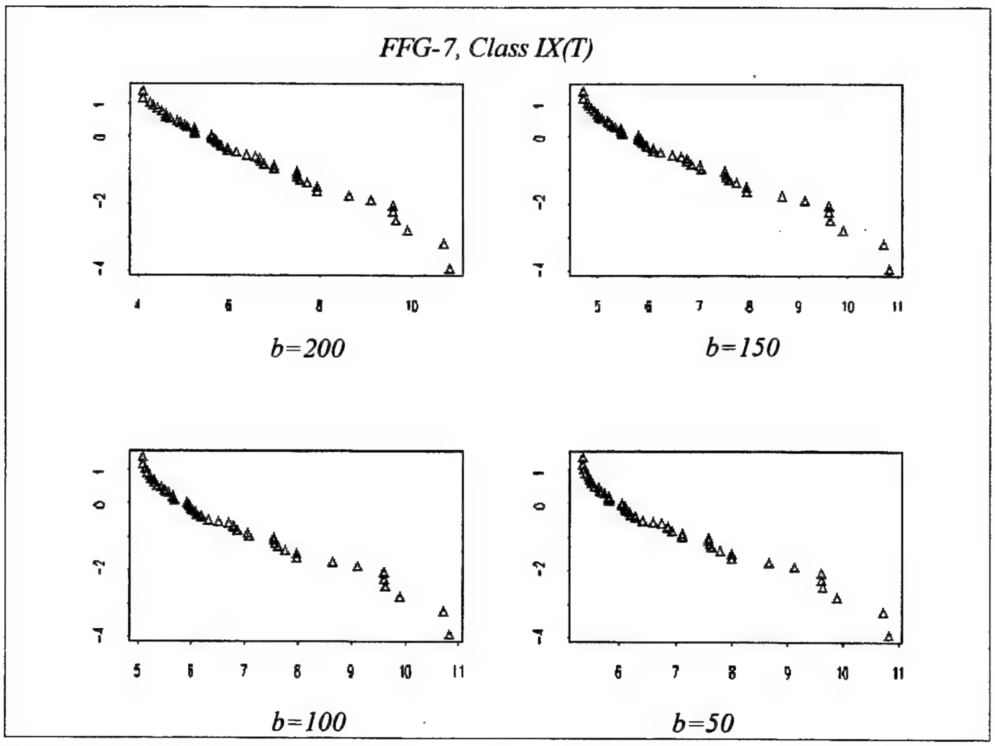

Figure D-1. Effects of varying parameter b to get a straight line.

Once the best value of b has been determined, the slope and intercept of the line are calculated. These values are used to find the values of the other two parameters in the EV distribution. A linear regression performed on the data provides the desired values, as is

demonstrated in Figure D-2:

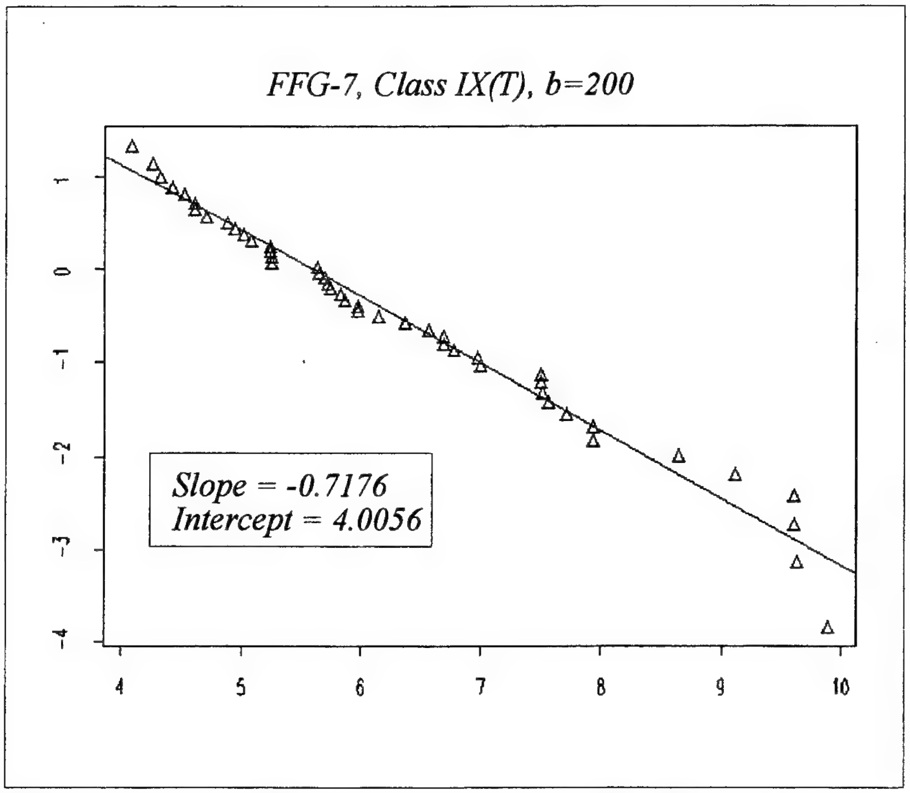

Figure D-2. Calculating slope and intercept for EV distribution.

Table D-1 displays all of the parameters for the EV distribution that were obtained by using this technique:

Class	b	Slope	Intercept	γ	a
CV IX(B)	2000	-1.7345	16.2961	1.7345	12,031.37
CV IX(G)	1000	-1.1432	12.9333	1.1432	81,901.27
CV IX(L)	60	-1.1115	5.2064	1.1115	108.215
CV IX(T)	3000	-0.7368	7.107	0.7368	15,456.20
CG IX(A)	4	-1.5918	6.6741	1.5918	66.208

Class	b	Slope	Intercept	γ	a
CG IX(B)	4000	-1.1409	10.6617	1.1409	11,411.37
CG IX(G)	3000	-1.0455	10.6797	1.0455	27,307.62
CG IX(T)	150	-0.6804	4.8051	0.6804	1,166.97
FFG IX(A)	5	-2.2851	8.8393	2.2851	47.858
FFG IX(B)	500	-1.4947	14.0345	1.4947	11,962.23
FFG IX(G)	500	-1.1502	11.8892	1.1502	30,842.14
FFG IX(M)	30	-2.3438	10.1485	2.3438	75.939
FFG IX(T)	200	-0.7176	4.0056	0.7176	265.586
DD IX(A)	25	-1.4927	5.4932	1.4927	39.648
DD IX(B)	500	-1.7373	15.0138	1.7373	5,664.82
DD IX(G)	500	-1.5651	16.3283	1.5651	33,953.66
DD IX(M)	25	-1.7403	7.769	1.7403	86.849
DD IX(T)	375	-0.6209	3.5883	0.6209	323.498

Table D-1. Parameters for EV Distributions Obtained by Ad Hoc Technique.

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